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## MODIFIED METHOD OF GEOMETRIC ELECTROMAGNETICS FOR THE ANALYSIS OF RADIO FIELD IN MARINE TROPOSPHERIC WAVEGUIDES

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The interest for practical use of tropospheric waveguides (TWG) above the sea surface is still high. This is because there are many new tools for remote sensing of the atmosphere boundary layer and efficient methods for calculation of radiowave fields. Those TWG often form over the Black Sea.

An efficient method for calculation of radiofields is the method of geometric electromagnetics (GE) based on the Brillouin conception. It has been used to determine radiofields and parameters of dielectrics waveguides and microwave devices [1]. The method GE had been developed for waveguiding systems with "rigid" boundaries of layered environment. However, a sea TWG is not a system with "rigid" boundaries. The first "wall" of TWG is the surface of the sea with parameters  $\varepsilon_3, \mu_3, \sigma_3$  that reflects incident radiowaves. The layer of atmosphere having a lower value of the relative dielectric permittivity  $\varepsilon_2$  will be the second "wall". At the same time in the TWG, up to the height,  $h_1$ , the permittivity  $\varepsilon_1$  varies to  $\varepsilon_2$  smoothly. If a superposition of plane waves (e.g., incident and reflected waves) satisfies the boundary conditions, then guided-wave propagation is possible. The equation for the resulting field in TWG accounts for this circumstance.

The Poynting vector  $\vec{\Pi}$  of a plane radio wave propagating in TWG (Fig.1) forms angles  $\theta_x, \theta_y, \theta_z$  with the axes of coordinates:

$$\cos^2 \theta_x + \cos^2 \theta_y + \cos^2 \theta_z = 1. \quad (1)$$

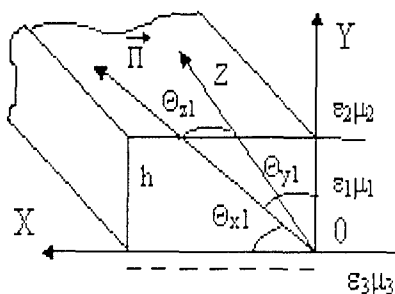


Fig. 1

At the height of TWG  $h_1$  the dielectric permittivity  $\varepsilon_1$  starts changing smoothly and reaches  $\varepsilon_2$  at the height  $h_2$ , hence to characterize the plane radio wave in the environment with a variable index of refraction we can use the equation,

$$E = E_m e^{j[\omega t - k(\cos\theta_x \cdot x + \cos\theta_y \cdot y + \cos\theta_z \cdot z)]} = E_m e^{j\left[\omega t - \frac{\omega}{c} n W_0(x, y, z)\right]}, \quad (2)$$

where  $\cos\theta_x$ ,  $\cos\theta_y$ ,  $\cos\theta_z$  are projections of the unit normal to wave's front, and  $n = \sqrt{\varepsilon}$  is the index of refraction. Equation for a smoothly varying environment is

$$W(x, y, z) = n W_0(x, y, z) = \text{const}, \quad (3)$$

where function  $W(x, y, z)$  is the eikonal:

$$\text{grad}(W) = n \text{ or } \left(\frac{\partial W}{\partial x}\right)^2 + \left(\frac{\partial W}{\partial y}\right)^2 + \left(\frac{\partial W}{\partial z}\right)^2 = n^2. \quad (4)$$

For TWG under consideration, the function  $W(x, y, z)$  can be simplified because  $\cos\theta_x = 0$ . The function  $W(y, z)$  might be presented as minimum of the linear integral  $\int n(S) dS$  taken from  $S = 0$  to  $S = h_1$ . The minimum is reached if the curve  $S$  coincides with the ray trajectory in troposphere:

$$\min \frac{1}{h_1} \int_0^{h_1} n(S) dS = \frac{1}{h_1} \int_0^{h_1} n(y) dy = \frac{W}{h_1}. \quad (5)$$

The equation (5) is used for determining the phase of radio waves reflected from the "upper wall" of TWG. A superposition of the incident wave and the reflected from the media interface yields the following electric field amplitude:

$$\begin{aligned} E &= E_m [\cos(\omega t + k_{y1} \cdot y - k_{z1} \cdot z) + \cos(\omega t - k_{y1} \cdot y - k_{z1} \cdot z + \varphi_h)] = \\ &= 2E_m \left[ \cos\left(k_{y1} \cdot y - \frac{\varphi_h}{2}\right) \cdot \cos\left(\omega t - k_{z1} \cdot z + \frac{\varphi_h}{2}\right) \right], \end{aligned} \quad (6)$$

where  $k_{y1} = k_1 \cdot \cos\theta_y$ ,  $k_{z1} = k_1 \cdot \cos\theta_z$ ,  $\varphi_h/2$  is the phase of the coefficient of reflection from the "upper wall" of TWG.

The equation (6) is valid under the conditions of total interior reflection of radio waves. As far as "upper wall" of TWG is "soft" (no "rigid" boundary between layers with  $\varepsilon_1$  and  $\varepsilon_2$ ), the current phase of the coefficient of reflection depends on the angles of incidence of radio waves and on the variation of the relative index of refraction:

$$M(y) = (\sqrt{\varepsilon(y)} - 1) \cdot 10^6 + \frac{y}{R_E} = [n(y) - 1] \cdot 10^6 + \frac{y}{R_E}, \quad (7)$$

where  $R_E$  is the radius of Earth,  $y$  is a current height of TWG for the waves with horizontal or vertical polarization, and the proper phase of the coefficient of reflection.

To account for the vector structure of the field it should be transformed to new system of coordinates,  $OX'$ ,  $OY'$ , and  $OZ'$ . This transformation is characterized with the Euler angles. If a radio wave has vertical polarization and  $\mu_1 = \mu_2 = 1$ ,  $\sigma_1 = \sigma_2 = 0$ , then we can write the final equation for  $\varphi_h/2$ :

$$\begin{aligned} \varphi_b = \frac{\varphi_h}{2} &= \arctg \left[ \frac{\varepsilon_1(y)}{\varepsilon_2(y) \cos \theta_{y1}} \cdot \sqrt{\sin^2 \theta_{y1} - \frac{\varepsilon_2(y)}{\varepsilon_1(y)}} \right] = \\ &= \arctg \left[ \frac{\frac{1}{h_1} \int_0^{h_1} n^2(y) dy}{\frac{1}{h_2} \int_{h_1}^{h_2} n^2(y) dy \cos \theta_{y1}} \times \sqrt{\sin^2 \theta_{y1} - \frac{\frac{1}{h_2} \int_{h_1}^{h_2} n^2(y) dy}{\frac{1}{h_1} \int_0^{h_1} n^2(y) dy}} \right], \quad (8) \end{aligned}$$

where  $n(y)$  is calculated after (7). The coordinate  $y$  varies from 0 through the inflection point of the profile  $M(y)$ , i.e.  $y = h_1$ , then to height  $h_2$  that is the coordinate of curve  $M(y)$  where the atmosphere is standard.

The value of  $\varphi_h/2$  obtained from (8) can be used in (6) to calculate the field both inside TWG and outside it at the heights from  $h_1$  to  $h_2$ . If dielectric permittivity of troposphere is complex-valued (conductance  $\sigma \neq 0$ ), then the equations (5)-(8) derived in this work can be used to calculate the energy losses in marine TWG.

The modified GE method that has been discussed in this work enables a more complete account of TWG effects during the waving. The evaluation of a frontier conditions by the "low wall" TWG above the Black Sea shows that radio waves with length about 10 cm experience almost specular reflection. The absolute value of the reflection coefficient is in the range of 0.87 to 0.95. The phase of reflection is  $\pi$  for the vertical and horizontal polarizations for "weak" and "strong" waveguides of evaporation having  $h_1 = 10$  m and near-surface TWG having  $h_1$  up to 500 m when the sea waving reaches 2 to 3 units [2].

Modification of the GE method allows estimation of important parameters of wave propagation in the TWG: wavelength, maximum phase and group velocities, critical angle  $\theta_{cr}$  limiting the range of wave propagation. The radiation patterns of radio devices must be oriented into angular sector that is determined by  $\theta_{cr}$ , therefore knowledge of  $\theta_{cr}$  has great practical value for proper feeding of TWG. Our theoretical results have been confirmed in radar experiments.

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